Threat Hazard Assessment - The Key to Insensitive Munitions

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ABSTRACT

One aspect of insensitive munitions technology that is required by MIL-STD-2105, yet whose methodology is still is ill-defined is the thread hazard assessment (THA). The THA requires definition of the statistical elements of exposure, likelihood, and probable consequences of damage. Current methodologies do not provide means to quantify the probabilities associated with the statistical elements of postulated threat scenarios so that they can be combined for risk assessment.

In this paper, the statistically-based threat hazard assessment methodology developed by Atlantic Research Corporation is presented. We discuss how system safety and risk analysis techniques are combined to develop a new procedure that provides quantitative measurement of system risks. The new methodology subdivides system risks into components for each threat scenario, life cycle event, and damage potential to all exposed platforms. This methodology rapidly identifies the primary contributors to system risk. As such, this methodology is useful as a design tool to rapidly evaluate risks of various design features. It is also useful as a management decision tool in evaluating risks, and can be extended to provide cost/benefit assessment.

Our methodology was programmed for a personal computer using spreadsheet mathematics to rapidly ascertain the effects of design changes on risks associated with exposure, likelihood, and possible consequences of damage. An example problem is presented for a missile system to show how our methodology assists in selecting the appropriate IM tests to conduct, and in defining system engineering solutions to produce an insensitive weapons system.

INTRODUCTION

An insensitive munition is defined to be a munition that reliably fulfills its performance, readiness, and operational requirements on demand, while minimizing the response and associated collateral damage when subjected to threats from unplanned heat, shock, or electromagnetic energy.

These threats are defined in a threat hazard assessment (THA) that determines the threats and hazards encountered by a munition during its cradle-to-grave life cycle. The THA includes both friendly and enemy threats, accidents, handling events, and other scenarios that occur. Where possible, it is based upon analytical results and historical or empirical data.

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The THA should include:

- o a review of pertinent historical safety experience,
- o a configuration description including material/thickness and energy source characteristics,
- o identification of requirements that the munition system will comply with relative to safety and environmental hazards,
- o cradle-to-grave life cycle profile,
- o identification of potential accident and combat threat scenarios at each life cycle step,
- o characterization of threat scenarios (stimuli level, duration, likelihood),
- o expected maximum allowed responses for each event,
- o estimated damage results and assessment on mission capability,
- o identification of problem areas where unacceptable reactions occur,
- o threat evaluation by risk assessment, and
- o determination of environmental tests and test configurations for the postulated threats.

System risks are identified by using the guidelines established in MIL-STD-2105B and MIL-STD-882B. The latter specification requires those hazards that produce unacceptable responses be reduced to an acceptable level. MIL-STD-882B also provides the following system safety precedence list (ranked from most-to-least importance) for this purpose:

- o design for minimum risk,
- o incorporate safety devices,
- o provide warning devices, and
- o improve or develop additional procedures and training.

Two THA approaches are currently being used. The first technique was developed by the Naval Air Warfare Center/China Lake. It begins with a defined life cycle profile and details the energy sources, restraints on energy release, threat stimuli, environments, expected and maximum allowed responses, a qualitative assessment of the frequency of threats and severity of responses, controls or mitigation that can be employed, and notes or pertinent comments. For the most part, the worksheet is filled out using a subjective engineering decision process. A worksheet has been developed to facilitate and standardize the documentation; an example of the worksheet for one life cycle event is presented in Table 1. Once the qualitative assessments have been performed for each life cycle step, the anticipated reactions are compared to the maximum allowable reaction. The maximum allowable damage is a reaction that allows loss of this weapon and perhaps adjacent weapons, but prevents propagation of the reaction and limits damage loss to a reasonable levels. Those events that result in reactions greater than the maximum allowable reaction are flagged as problems. The problems are subsequently ranked by risk assessment factors defined in MIL-STD-882B. A second approach is based upon a cost/benefit analysis of the anticipated responses and collateral damages that occur with a given weapon system. The total expected value of the fleet before and after the munitions response is determined, and calculations are repeated with potential mitigation or design fixes to assess the benefits in terms of cost.

There are several limitations to both approaches that restrict their usefulness. The first approach is qualitative, and therefore not readily coupled with quantitative risk assessment methods. Furthermore, the user accumulates an exceedingly detailed and lengthy packet of data (a typical munition may have over 100 different life cycle steps, with one worksheet addressing each step for each potentially damaging energetic compound in the munition system). The voluminous data that are compiled prevent rapid and easy use as a management assessment tool or as a design risk assessment program. The second technique is qualitative, at least in terms of estimating costs (damage severity). Its main detraction is that it deals with only one aspect of the life cycle rather than the complete cradle-to-grave profile. Extensive data would need to be gathered, collated, and correlated before the second technique could be extended to perform life cycle assessments. Lastly, costs can be very subjective, and other factors such as weapon operational readiness may be more important.

We have coupled system safety with risk analysis techniques to develop a quantitative THA methodology that addresses the aforementioned limitations of the current methods. Use of risk analysis techniques allows the user to characterize the total system risk in terms of contribution from each threat, life cycle event, or platform damage potential. This allows the user to identify the predominant threats and quantify the contributions from each component. We have implemented this methodology into a spreadsheet and graphic display for rapid evaluation, thereby producing a tool that provides assistance in making management decisions, and as a design aid in evaluating alternate designs or mitigation features.

DISCUSSION

METHODOLOGY

Risk analysis requires determining the probabilities of parameters that govern the frequency of occurrence and damage severity. THA requires that these probabilities be defined for each hazardous explosive component at each step in the cradle-to-grave life cycle, and for each type of threat that is possible for a given life cycle step.

For a given life cycle step, a likelihood of exposure, L_{ei}, of each explosive component in a munition to pertinent threats can be defined as the product of the probability of occurrence of a given life cycle step (E_{ei}) and the probability of each threat to occur in that life cycle step (p_{ei}).

$$L_{e_i} = E_{e_i} * p_{e_i} \tag{1}$$

E_{ei} is simply the fraction of time that the munition is in that life cycle step.

$$E_{e_i} = \frac{t_i}{\sum t_i} \tag{2}$$

The probability of threat occurrence, p_{ei}, is ideally defined from a compendium of hazards occurrence data. We have used engineering estimates to develop preliminary estimates of p_{ei} for a variety of life cycle events, including both peacetime and wartime scenarios. An example of a p_{ei} for truck transportation within the continental United States is shown in Table 2. A life cycle profile of a generic munition, depicted in Figure 1, was combined into twelve broad life cycle categories. The probability of exposure of each broad life cycle category is presented in Table 3.

Table 2. Probability of Exposure to Equivalent Threats for Truck Transportation, Continental United States (Peacetime).

THREAT STIMULI	EQUIVALENT ENVIRONMENT						
	FCO	SCO	SD	BI	FI	SCJI	SCSI
Transfer/Handling Damage	0	0	5	0	0	0	0
Terrorist Activity	55	0	5	20	20	0	0
Improper Equipment	10	0	0	0	0	0	0
Fire	75	20	5	0	0	0	0
Collision	50	0	5	25	20	0	0
Enemy Action	0	0	0	0	0	0	0
Normalized Total, p_{ei}	60.4	6.3	6.3	14.3	12.7	0	0

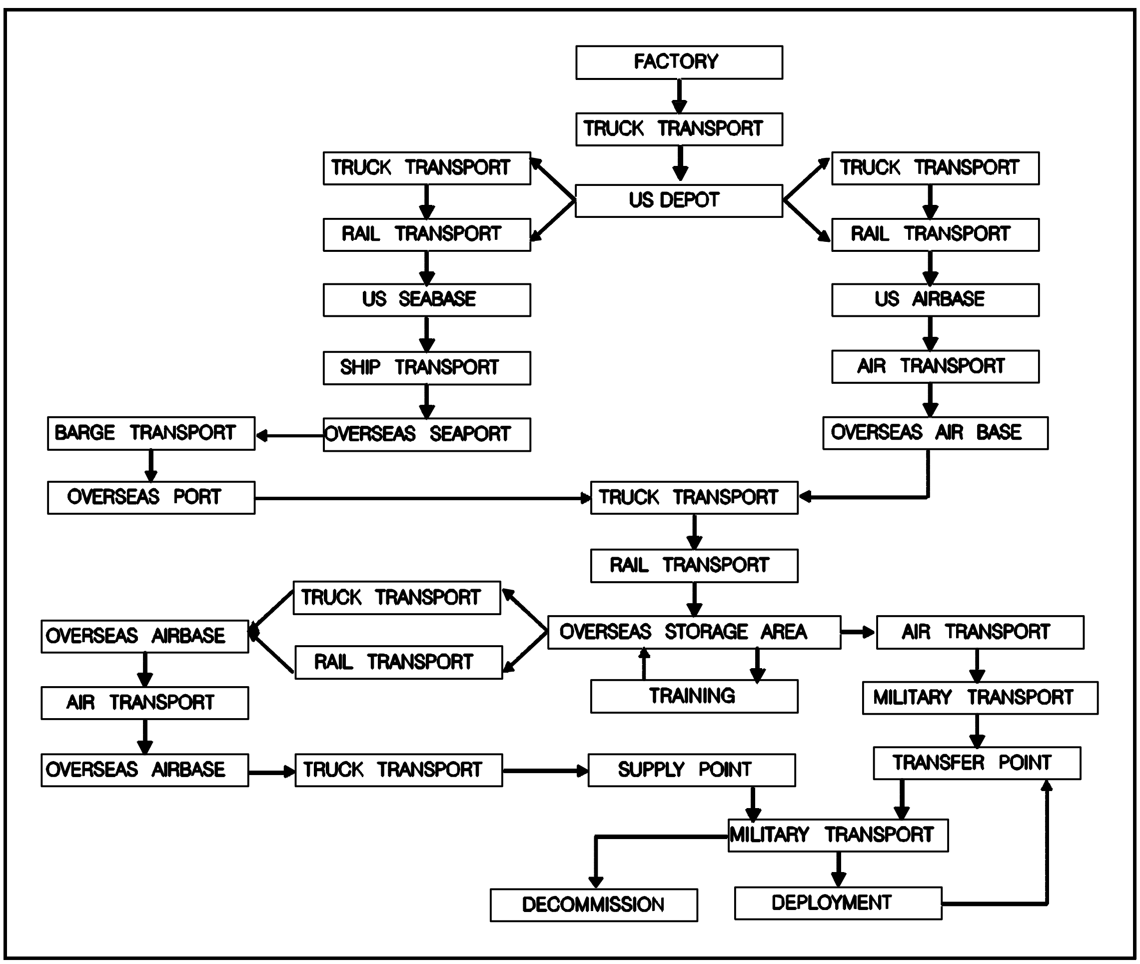

Figure 1. Cradle-to-Grave Life Cycle.

Table 3. Probabilities of Exposure for each Life Cycle Category.

Life Cycle Category	Fraction of Life	Life Cycle Category	Fraction of Life
Storage, US	0.43292	Overseas Storage	0.47410
On/Off Load, US	0.00095	Overseas On/Off Load	0.02288
Truck Transport, US	0.00458	Overseas Truck Transport	0.00648
Flatcar Transport, US	0.01068	Overseas Flatcar Transport	0.02212
Ship/Barge Transport	0.01525	Mil Transport	0.00775
Aircraft Transport	0.00229	Operational Use	0.00001

The probabilities of occurrence (P_O) and the damage severity (P_D) are obtained from the THA worksheets as a function of life cycle step and estimated platform damage. Ideally, these probabilities are obtained from safety, hazard, and accident databases. Probability estimates based on risk analyses can be used when such data are not available. Risk analyses assume that both frequencies of occurrence and damage severity categories vary logarithmically, reflecting real world accident statistics. The validity of this assumption is readily apparent if accident cost data are reviewed. Damage costs can vary from negligible (less than $\$10^3$) to more than $\$10^9$ for major carrier accidents[I]. In this present work, we assumed one order of magnitude variation between frequency of occurrence categories. Due to the small number of damage severity categories, two orders of magnitude between damage was used. The product of the two probabilities, as defined in MIL-STD-882B's risk matrix (Table 4), is used to quantify these values. Ratings for each category are obtained from the THA worksheets.

Table 4. Frequency and Damage Severity Risk Matrix.

Frequency	Severity			
	1 Catastrophic	**2 Critical**	**3 Occasional**	**4 Negligible**
A Frequent	1A	2A	3A	4A
B Probable	1B	2B	3B	4B
C Occasional	1C	2C	3C	4C
D Remote	1D	2D	3D	4D
E Improbable	1E	2E	3E	4E

The bold lines divide Table 4 into three decision regions. From top-to-bottom, these regions represent unacceptable levels of risk, levels of risk that require management decision, and acceptable levels of risk.

The risk corresponding to a threat for one explosive component of a munition that results in a given damage for a given life cycle is:

$$P(RISK)_{i,j,k} = P_{O_{i,j,k}} * P_{D_{i,j,k}} * E_{e_i} * p_{e_{i,j}} \tag{3}$$

The ijk subscripts correspond to life cycle step, threat, and damage categories (note that a fourth subscript is required if more than one munition component is included in the analyses). The total risk for the explosive component is calculated by assuming that the separate risks for each threat, damage category, and life cycle are independent. This assumption allows the use of Boolean algebra to sum up individual risks as shown in (4) to (7).

$$Probability\,of\,Life\,Cycle\,Induced\,Risk:\; P(RISK)_{LC} = 1-\prod_i (1-P_{risk_{ijk}}) \tag{4}$$

$$Probability\,of\,Threat:\; P(RISK)_T = 1-\prod_j (1-P_{risk_{ijk}}) \tag{5}$$

$$Probability\,of\,Damage\,Severity:\; P(RISK)_D = 1-\prod_k (1-P_{risk_{ijk}}) \tag{6}$$

Total risk for the explosive component of the munition can be calculated by summing the individual risk totals for each damage category, threat, and life cycle.

$$Total\,Risk\,Probability:\; P(RISK)_{TOTAL} = 1-[(1-P(RISK)_{LC}) * (1-P(RISK)_T) * (1-P(RISK)_D)] \tag{7}$$

Application - Risk Analysis Management Tool

This methodology was applied to a missile system subjected to the life cycle profile summarized in Table 3. Ranges of damage severity and frequency categories through the life cycle for each damage category as estimated in the worksheets are shown in Table 5. The methodology was programmed into a spreadsheet for rapid computations. The results are presented for two components of the missile (warhead and booster).

Figure 2 shows the risks for both explosive components as a function of life cycle category. Figure 3 plots the risk as a function of the fraction of time for that life cycle step (E_{ei}). The nonlinear behavior shows that the higher damage or more frequent occurrence can outweigh long exposures (such as occurs during storage).

Figure 4 shows the risks as a function of each damage category. The greatest risks are to personnel. Two orders of magnitude lower is the risk to the missile launcher. The other damage categories are another two orders of magnitude lower than missile launcher risks. This shows that significant risk reductions can be readily accomplished by minimizing the exposure of personnel to the missile.

Table 5. Damage and Frequency Rating Range for Each Damage Category.

Damage Category	P_O / P_D	Damage Category	P_O / P_D
Canister	2 / D to 2 / A	Milvan	2 / C
Personnel	1 / A to 1 / D	Transport Vehicle	2 / C to 2 / D
Equipment	3 / D	Ship/Barge	2 / D
Facilities	2 / D	Aircraft	2 / D
Flatcar	2 / D	GMT/LS	2 / D

Note: Refer to Table 4 for rating definitions.

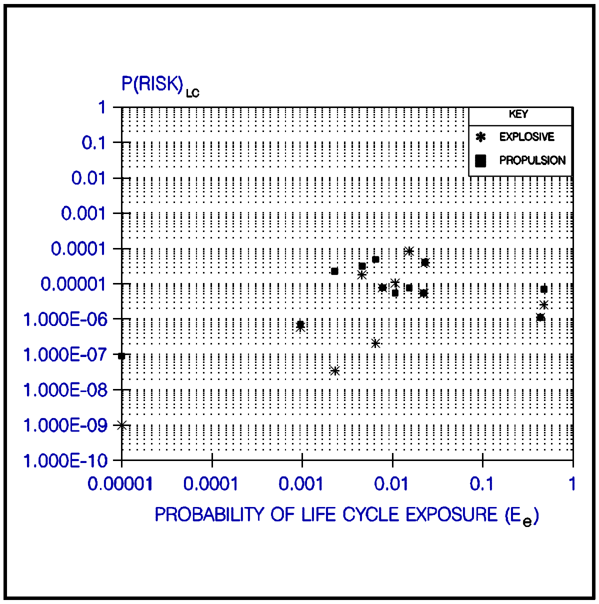

Figure 2. Risk Compared to Fraction of Life Cycle.

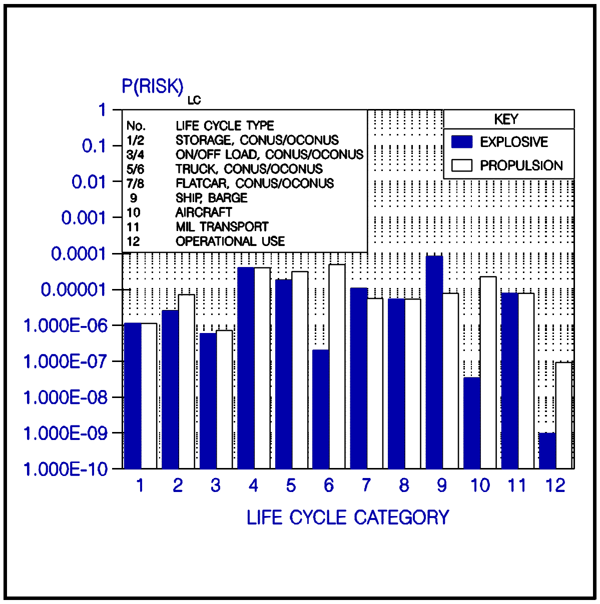

Figure 3. Risk for Each Life Cycle Category.

Figure 5 shows the risks as a function of equivalent threat. It is obvious that risk reduction should focus on addressing fast cookoff (FCO), bullet impact (BI), and fragment impact (FI) threats for both the warhead and propulsion systems, and on slow cookoff (SCO) for the warhead. Figure 6 shows the total risk for both explosive components. The propulsive system is shown to create greater risks than the relatively insensitive warhead, and that risk reduction efforts should be concentrated on FCO, BI, and FI threats on the booster.

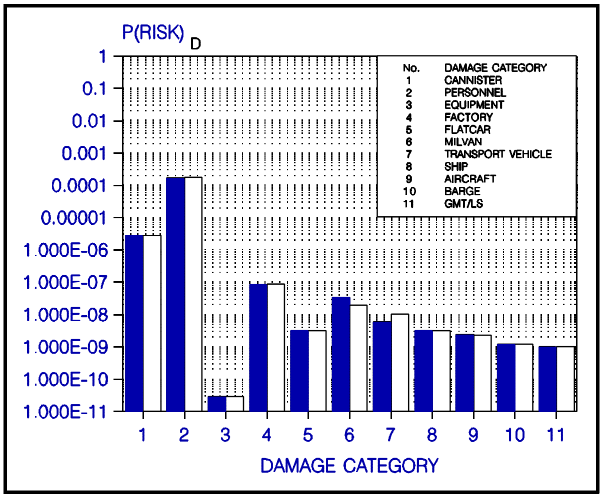

Figure 4. Risk for Each Damage Category.

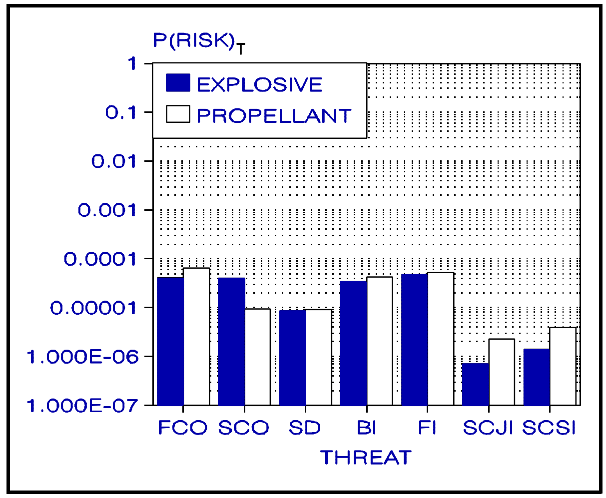

Figure 5. Risk for Each Equivalent Threat.

Application - Design Trade Study Tool

The most important system safety approach identified in MIL-STD-882B is to design for minimum risk. This entails knowing on an apriori basis the risks associated with conceptual design, and the effect of design changes on risk levels. The proposed methodology, when implemented in a spreadsheet format, allows rapid evaluation of design changes.

Table 6 lists some mitigation features for a propulsion system, and the estimated change they induce in the probabilities for frequency and severity. The reduction in risk for the propulsion system as a function of the threat with these mitigation features is readily evaluated as shown in Figure 7. Combinations of design features that allow the risks to be reduced to below the acceptable level are readily identified.

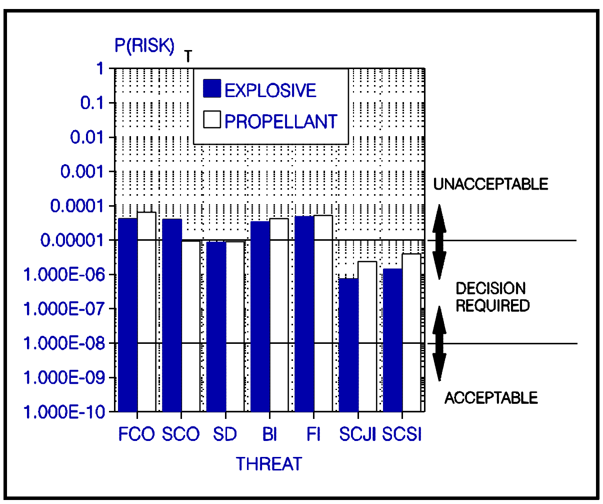

Figure 6. Baseline Total System Risks.

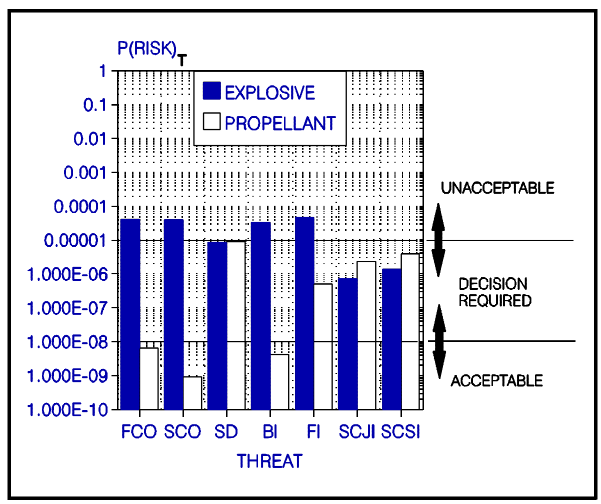

Figure 7. Effect of Active Mitigation Device on System Risks.

Table 6. Estimated Effect of Mitigation Features on Damage Severity and Frequency Probabilities.

Mitigation Concept	Threat Addressed	Probability Affected	Categories Changed
External protection vest	BI/FI	P(I)	2/1
Case redesign - Low temp. composite	FCO/SCO	P(I)	2/0
Reduced propellant sensitivity	BI/FI	P(I)	1/1
Propellant bore filler	BI	P(I)	1/0
Thermite Charge	FCO/SCO	P(C/I)	1/2
Thermal/pressure-initiated venting system	FCO/SCO/BI/FI	P(C/I)	2/2/2/1

CONCLUSIONS

Current THA methodologies are either qualitative and cannot be readily coupled with risk assessment methods, or deal with only one aspect of the life cycle rather than the complete cradle-to-grave profile. A life cycle-based THA methodology was developed that provides quantitative measurement of system risks in terms of the components for each threat scenario, life cycle event, and damage potential to exposed platforms. This methodology was demonstrated to rapidly identify the primary contributors to system risks, and was shown to be useful as a design tool in evaluating risks of various designs. The methodology can readily be broadened into a management decision tool for cost/benefit assessments provided that accurate accident and cost data and test data become available.

Reference:

I. Fontenot, J. S. and Dettling, R. F., "A Cost/Benefit Analysis of Insensitive Munitions Using Historic Mishap Data," in **CPIA Pub. 562**, pp 15-22, March 1991.